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SAFETY CONSIDERATIONS AND BIOLOGICAL HAZARDS OF THE NEAR-MILLIM--ETC(U)

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Safety Considerations and Biological Hazards of the Near-Millimeter Wave Region

by Edward A. Brown

U.S. Army Electronics Research
and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783

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This report is an annex to the Near-Millimeter Wave Technology Base Study. It contains a survey of the most recent literature dealing with the question of biological hazards that may be encountered while working with sources of near-millimeter wave (NMMW) radiation. There is currently a severe lack of data in the NMMW frequency region (100 to 1000 GHz). Thus, most of the conclusions take the form of

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20. Abstract (Cont'd)

extrapolations from work done at lower frequencies. The highly controversial issue of possible nonthermal effects is considered.

FOREWORD

This report was originally drafted to be included as a chapter in the components volume of the Near-Millimeter Wave Technology Base Study. However, it was decided to publish this material separately to call attention to this relatively unexplored area. As the near-millimeter wave technology grows and with it the number and the power of NMMW sources, the laboratory researcher must be aware that there is a possibility of certain radiation hazards. It is the purpose of this volume to summarize some of the current research relating to the potential hazards.

I would like to acknowledge the many fruitful discussions with Stanley M. Kulpa of the Harry Diamond Laboratories during the preparation of this report. Dr. Kulpa and I cochaired the Near-Millimeter Wave Technology Base Study Panel during 1977. The interest in the NMMW technology generated by the results of the panel meeting and the program planning efforts that followed provided the motivation for gathering the data in this report.

I also wish to thank Howard E. Brandt, also of the Harry Diamond Laboratories, for his review of this manuscript and his helpful suggestions.

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1. INTRODUCTION

Even though work in the millimeter wave and near-millimeter wave (NMMW) spectral regions has been carried out for many years, it is only recently that there has been a very rapid growth in research and development programs. This rapidity is due in part to an increased Government interest, especially by the Department of Defense, the Department of Energy, and the National Aeronautics and Space Administration. Along with the growth in these programs has come a proliferation of sources of increasingly higher powers. Thus, it is appropriate that as the NMMW state of the art advances, the safety considerations presented by this new technology should be recognized.

There are some obvious hazards to which an experimenter should be alert. For instance, the hazards of high voltage (~10 kV) equipment fall into two categories: electrical and x-radiation. Safeguarding against electrical shock can be accomplished only by designing the equipment so that the probability of personnel ever coming into contact with conductors at high potentials is essentially nonexistent. Items such as proper grounding, interlocks, warning lights, and automatic capacitor discharging schemes are basic to proper safety design. Normally, they do not significantly increase the size or the weight of the equipment.

Shielding against x-ray emission from high voltage equipment essentially involves attenuation of the radiation by surrounding the source with a sufficient amount of absorbing material. The amount of material needed increases rapidly with operating voltage. Table 1 gives typical thicknesses of lead and concrete required as a function of voltage for an electron gun operating at a 100-W average power in order to reduce the exposure at 1 m to 3 mR/hr.

TABLE 1. REQUIRED SHIELDING FOR HIGH-VOLTAGE EQUIPMENT

Voltage (kV)	Shielding: Lead (mm)	Shielding: Concrete (cm)
50	0.4	5.1
70	1.3	12.7
100	2.4	17.8
150	3.0	25.4
200	4.5	33

In addition, many of the lasers utilize highly toxic or corrosive gases. The hydrogen cyanide (HCN) laser immediately comes to mind along with those lasers using halogenated gases. The handling of these gases obviously requires care to avoid exposure of personnel. Another safety consideration involving the laser is the carbon dioxide (CO_2) pump laser used to excite the NMMW gas cell.* The pump usually has sufficient power to cause eye damage, and thus goggles must be worn whenever the laser is operating.

These types of hazards are not unexpected, and techniques have been evolved to deal with them. However, there is a whole class of hazards that is unique to working in this portion of the spectrum and that only recently has begun to receive consideration. This is the biological hazard posed by exposure to the radiation itself, even at modest power levels.

As is the case with most other aspects of NMMW technology, there is a dearth of information on radiation hazards above 100 GHz. Proceeding downward in frequency through the millimeter region to microwaves, the number of data increases greatly. For example, there is a large body of data at 2.45 GHz, where microwave ovens operate. Clinical, statistical, and theoretical studies abound at these lower frequencies. In this report, the extrapolation of these data and theories to the NMMW region is discussed, and the major issues as well as they are now understood are surfaced. There is no attempt to discuss in detail the large body of low frequency data. The purpose of this report is to acquaint the reader with the possible radiation hazards and the issues that surround them so that proper caution may be exercised in the conduct of NMMW experiments.

It should be noted at the outset that those working in this field today are embroiled in a major controversy that has caused a strong polarization of opinion. The issue is whether the hazard to living organisms from radiation is purely thermal in nature or includes appreciable nonthermal effects as well. The thermal effects are due quite simply to the absorption of energy from a radiating source and the resultant damage from the heating of the body tissues. This damage can be superficial resembling a sunburn, deep-lying cellular disruption at a specific site such as what occurs when a piece of meat is cooked in a microwave oven, or an overall raising of the body temperature similar to a fever. There is no question but that these thermal effects are real. The controversy is whether there are detrimental effects that occur in

**This consideration does not apply to the directly excited HCN laser.*

living organisms at powers lower than those necessary to cause thermal damage. At the center of this controversy is the issue of what the safety standard for exposure to this radiation should be. Currently, the U.S. standard is 10 mW/cm^2, which is three orders of magnitude higher than the standard set by the Soviet Union. Not surprisingly, it is the Soviets that are the strongest proponents for the existence of nonthermal effects, although there are an increasing number of supporters of this view in the United States.

The conclusion reached during this brief examination of the existing data and theories is that nonthermal effects, while difficult to quantify, should by no means be dismissed out of hand. Moreover, even though the coupling of higher frequency radiation into the body appears at first glance to be severely limited by the skin effect, this also should not be accepted without further question into the possibility of resonances with smaller external body parts and cavities.

2. THERMAL EFFECTS: GENERAL

In the United States, the Occupational Safety and Health Administration (OSHA) has established a safety level of 10 mW/cm^2 incident electromagnetic power density for frequencies between 10 MHz and 100 GHz averaged over a 6-min period.[1] This level, promulgated in OSHA Standard 29 CFR part 1910.97, is essentially in agreement with the standard set by the American National Standards Institute ANSI C95.1-1974.[2] These standards are based on what is perceived to be the acceptable thermal burden as calculated for humans.

Every animal generates heat in proportion to its metabolic rate. The deposition of electromagnetic energy in the tissues produces an additional heat loading either in a localized area or as an overall rise in body temperature. Localized heating is dissipated by blood circulation, the result being a generalized hyperthermia. Depending on the species, excessive heating is eliminated by various mechanisms such as sweating and panting.[3] The OSHA and ANSI standards are based on the concept that the electromagnetically induced heat load should not exceed the basal metabolic rate (expressed in watts).

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[1]*Occupational Safety and Health Administration Standard 29 CFR Part 1910.97.*

[2]*Safety Level of Electromagnetic Radiation with Respect to Personnel, American National Standards Institute ANSI C95.1-1974 (1974).*

[3]*C. H. Durney, C. C. Johnson, P. W. Barber, H. Massoudi, M. F. Iskander, J. L. Lords, D. K. Ryser, S. J. Allen, and J. C. Mitchell, Radiofrequency Radiation Dosimetry Handbook, 2nd ed., University of Utah, Salt Lake City, UT, SAM-TR-78-22 (May 1978).*

Basically, the body has two physiological mechanisms that it calls upon to deal with heat stress. The first mechanism is an increased sweat rate to increase evaporative cooling. The second mechanism is vasodilation, which shunts warm blood from the body core to the skin. This raises the skin temperature and causes an increase in evaporative cooling and a decrease in heat gain through radiation and convection. The behavior of both of these mechanisms is a complex function of many variables such as the body's physical characteristics (height, weight, and surface area) and the characteristics of the surrounding environment (wind velocity, ambient temperature, and relative humidity). Calculations have been done based on an overall heat transfer equation. The equation calculates the rate of heat storage in the body as a function of the metabolic rate; the rate of external work; the rates of heat transfer by evaporation, convection, and radiation; and the amount of electromagnetic power absorbed.[3]

A maximum amount of heat storage allowable for a human has been determined to be that amount causing a rectal temperature rise of 2.2 deg C from a normal rectal temperature of 37 to 39.2 C. (This critical temperature was arrived at as a useful standard by several researchers. It is not the result of any particular set of empirical or theoretical data.) For each degree of rise above normal, the basal metabolic rate increases by as much as 14 percent. This increase demands an increase in blood circulation and respiration, as well as a 50- to 100-percent increase in the supply of oxygen to the tissues to maintain cellular activity. The condition is aggravated by the reduced capability of hemoglobin to combine with oxygen and by the increased circulation rate, which reduces the time available for oxygen transfer in the lungs. An excessive rise in body temperature due to microwave irradiation produces tissue damage indistinguishable from that produced by fever of any origin. Pathological changes found at autopsy when death was due to severe hyperpyrexia include diffuse degenerative changes throughout the body; myocardial degeneration and necrosis; and hemorrhagic lesions in the gut, the respiratory tract, the liver, and the brain. Fatally exposed animals develop acidosis, hyperpnea, and tetany and die of respiratory arrest.[4]

Calculations of the heat balance equation have been carried out by using accepted values of the various heat transfer rates. For example, the normal human has a maximum sweat rate of over 2 liters/hr, which is equivalent to 1345 W of cooling power. These calculations mean that,

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[3]*C. H. Durney, C. C. Johnson, P. W. Barber, H. Massoudi, M. F. Iskander, J. L. Lords, D. K. Ryser, S. J. Allen, and J. C. Mitchell, Radiofrequency Radiation Dosimetry Handbook, 2nd ed., University of Utah, Salt Lake City, UT, SAM-TR-78-22 (May 1978).*

[4]*W. Moore, Biological Aspects of Microwave Radiation: A Review of Hazards, U.S. Department of Health, Education, and Welfare TSB-68-4 (July 1968).*

under most conditions of severe thermal stress, evaporative cooling is limited by evaporation rate and not sweat rate. The results of these calculations have been plotted to show the maximum rate at which power can be absorbed by a human. These plots have been parameterized to show the effects of temperature, humidity, wind, amount of clothing, and activity of the subject. For any particular set of these parameters, the heat storage by the body can be equated to the electromagnetic power absorbed. An example of such a plot is shown in figure 1. The ordinate, marked SAR_{60}, is the specific absorption rate (in watts per kilogram of body weight) that would produce a rectal temperature of 39.2 C in the irradiated subject in 60 min. The plot is intended to represent the maximum SAR that a healthy man can tolerate with regard to thermal considerations for 1 hr in a given environment, both assuming a normal capacity for thermoregulation and assuming that the other criteria concerning metabolic rate, posture, clothing, and behavior are as stated.[3]

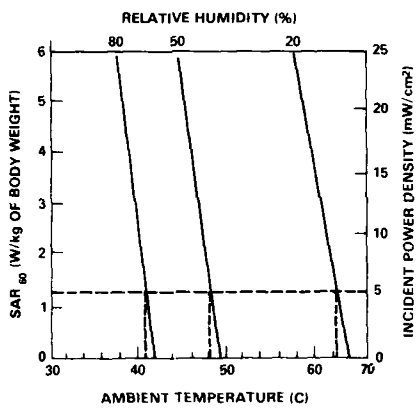

Figure 1. Calculated values of specific absorption rate that, in 60 min, would produce a rectal temperature of 39.2 C in an average man, unclothed and sitting quietly, irradiated by an electromagnetic plane wave with E-polarization at resonance (about 70 MHz) (from C. H. Durney et al, University of Utah SAM-TR-78-22, May 1978).

The curves shown in figure 1 show the worst possible case for a human, which is, according to the data calculated by using the prolate spheroidal model, E-polarization at resonance (about 70 MHz)--that is, the electric field vector parallel to the long axis of the body with a frequency corresponding to about 2 m, or the height of an average man. The intercept of the curves with the abscissa indicates the ambient conditions that produce a rectal temperature of 39.2 C with no irradiation. For example, at a relative humidity of 80 percent and an

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[3]*C. H. Durney, C. C. Johnson, P. W. Barber, H. Massoudi, M. F. Iskander, J. L. Lords, D. K. Ryser, S. J. Allen, and J. C. Mitchell, Radiofrequency Radiation Dosimetry Handbook, 2nd ed., University of Utah, Salt Lake City, UT, SAM-TR-78-22 (May 1978).*

ambient temperature of 42 C, the SAR_{60} is 0, meaning that in 1 hr the critical body temperature is reached with no additional heat loading by an electromagnetic energy source. If the ambient temperature were to drop to 41 C, however, the SAR_{60} would be 1.25 W/kg, which, all other things being held constant, would imply an incident power density of 5 mW/cm^2.

The value of the incident radiation's frequency now becomes of interest in the discussion. At resonance, the absorption by the body is maximum. At very high frequencies, where the wavelength of the incident radiation is very small compared with the size of the body, the concepts of geometrical optics apply. That is, the electromagnetic waves can be thought of as rays. In this case, for lossy bodies, the effects are mostly surface effects, because the depth of penetration decreases rapidly as frequency increases. This is the skin effect. The skin depth depends on both conductivity and frequency. At 10 GHz, for example, the skin depth in tissue is less than 0.5 cm. At such high frequencies, the fields in one part of the body are affected only very slightly by other parts of the body. Table 2 shows the skin depth in biological tissue for various frequencies. The numbers are given for a plane wave incident on the surface of a semi-infinite dielectric slab and thus can be used only to give a rough idea of the depth of penetration in an absorber such as a spheroid. The skin depth values are calculated from the equation

$$\delta = \frac{67.52}{f}\left[\sqrt{(\varepsilon')^2 + (\varepsilon'')^2} - \varepsilon'\right]^{-1/2} \quad \text{(meters)} \quad ,$$

where f is the frequency in megahertz and ε' and ε'' are the real and imaginary parts[3] of the relative electric permittivity (which are themselves frequency dependent). The values of the skin depth shown in table 2 are plotted in figure 2. Note that table 2 gives values of the skin depth calculated for tissues having permittivities of two-thirds those of muscle. This calculation was done to give a whole body average value over tissues of high water content such as muscle and skin and tissues of low water content such as bone and fat. Table 3 displays these values for both types of tissues. Note that propagation through low water content tissue is almost an order of magnitude greater than that through high water content tissue.[5]

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[3] *C. H. Durney, C. C. Johnson, P. W. Barber, H. Massoudi, M. F. Iskander, J. L. Lords, D. K. Ryser, S. J. Allen, and J. C. Mitchell, Radiofrequency Radiation Dosimetry Handbook, 2nd ed., University of Utah, Salt Lake City, UT, SAM-TR-78-22 (May 1978).*

[5] *S. Baranski and P. Czerski, Biological Effects of Microwaves, Dowden, Hutchinson, and Rose, Inc., Stroudsburg, PA (1976).*

TABLE 2. RADIATION SKIN DEPTH IN BIOLOGICAL TISSUE (TWO-THIRDS MUSCLE PERMITTIVITY)

Frequency (MHz)	Skin depth* (cm)
1	91.33
10	26.14
27.12	17.36
40.68	13.59
100	8.04
200	4.87
300	4.14
433	3.72
750	3.20
915	3.02
1,500	2.66
2,450	2.06
3,000	1.79
5,000	1.09
7,500	0.61
10,000	0.41
100,000	0.059

**From C. H. Durney et al, University of Utah SAM-TR-78-22 (May 1978).*

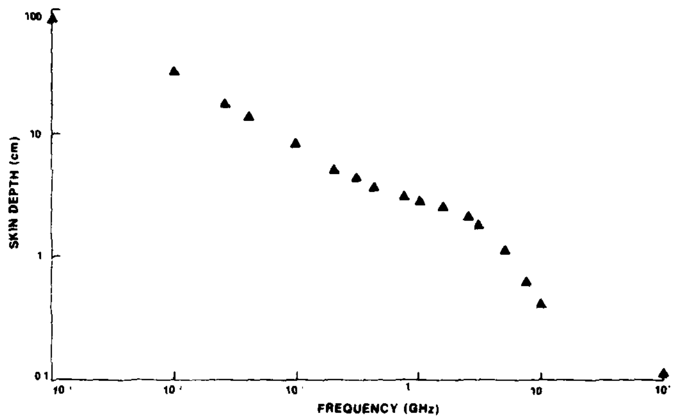

Figure 2. Radiation depth through skin in biological tissue (two-thirds muscle permittivity).

Thus, in the NMMW region, the penetration into human tissue is reduced by a factor of 1/e within 0.5 mm at best at the lowest frequency of interest, 100 GHz. At higher frequencies, the dropoff is even faster. We may, therefore, feel safe to conclude that the direct penetration of NMMW radiation to deeper-lying organs occurs only at powers sufficiently high to cause severe superficial burning similar to a sunburn. This superficial burning thus provides a warning of present danger to the individual. At lower powers, the dropoff is sufficient to dissipate the energy in the outermost layers of the skin.

There is one other facet of this argument that should be noted, at least for the record. While this discussion has assumed that the only resonance coupling of radiation to the body will occur at about 70 MHz, in fact there may be resonances at higher frequencies corresponding to the smaller dimensions of the body. The ear canal could represent a path for direct coupling to the brain at a frequency in the tens of gigahertz, which corresponds to dimensions of the order of 1 cm. While this facet is just speculation, should it prove to have any validity, the conclusions as to the hazard of NMMW radiation would have to be reevaluated.

TABLE 3. CHARACTERISTICS OF ELECTROMAGNETIC WAVE PROPAGATION

Tissue water content	Frequency (MHz)	Wavelength air/tissue (cm)	Depth of penetration (cm)	Dielectric constant	Conductivity (mho/cm)	Reflection coefficient			
						Air-muscle interface		Muscle-fat interface	
High (skin and muscles)	100	300/27	6.66	71.7	0.889	0.881	+175	0.650	-7.96
	200	150/16.6	4.79	56.5	1.28	0.844	+175	0.612	-8.06
	300	100/11.0	3.89	54	1.37	0.825	+175	0.592	-8.14
	433	69.3/8.76	3.57	53	1.43	0.803	+175	0.562	-7.06
	750	40/5.34	3.18	52	1.54	0.779	+176	0.532	-5.69
	915	32.8/4.46	3.04	51	1.60	0.772	+177	0.519	-4.32
	1,500	20/2.81	2.42	49	1.77	0.761	+177	0.506	-3.66
	2,450	12.2/1.76	1.70	47	2.21	0.754	+177	0.500	-3.88
	3,000	10/1.45	1.61	46	2.26	0.751	+178	0.495	-3.20
	5,000	6/0.89	0.788	44	3.92	0.749	+177	0.502	-4.95
	5,800	5.17/0.775	0.720	43.3	4.73	0.746	+177	0.502	-4.29
	8,000	3.75/0.578	0.413	40	7.65	0.744	+176	0.513	-6.65
	10,000	3/0.464	0.343	39.9	10.3	0.743	+176	0.518	-5.95
Low (fat and bone)	100	300/10.6	60.4	7.45	19.1-75.0	0.511	+168	0.650	+172
	200	150/59.7	39.2	5.95	25.8-94.2	0.458	+168	0.612	+172
	300	100/41	31.1	5.7	31.6-107	0.438	+169	0.592	+172
	433	69.3/28.8	26.2	5.6	37.9-118	0.427	+170	0.562	+173
	750	40/16.8	23	5.6	49.8-138	0.415	+173	0.532	+174
	915	32.8/13.7	17.7	5.6	55.6-147	0.417	+173	0.519	+176
	1,500	20/8.41	13.0	5.6	70.8-171	0.412	+174	0.506	+176
	2,450	12.2/5.21	11.2	5.5	96.4-213	0.406	+176	0.500	+176
	3,000	10/4.25	9.74	5.5	110-234	0.406	+176	0.495	+177
	5,000	6/2.63	6.67	5.5	162-309	0.393	+176	0.502	+175
	5,900	5.17/2.29	5.24	5.05	186-338	0.388	+176	0.503	+176
	8,000	3.75/1.73	4.61	4.7	255-431	0.371	+176	0.513	+173
	10,000	3/1.41	3.39	4.5	324-549	0.363	+175	0.518	+174

Source: S. Baranski and P. Czerski, Biological Effects of Microwaves, Dowden, Hutchinson, and Rose, Inc., Stroudsburg, PA (1976), 50.

3. EXPOSURE OF CRITICAL ORGANS TO NMMW RADIATION: THERMAL EFFECTS

Apart from the above consideration of hypothermic reactions of the whole body to non-ionizing radiation, one must also realize that certain organs of the body are particularly susceptible to damage that is probably thermal in nature.

The mode of action of non-ionizing electromagnetic radiation on biological tissue is often through its interaction with the polar molecule water. As the microwave field oscillates, the water molecules are caused to vibrate and thus generate heat. Thus, it is understandable that the greatest absorption of microwaves and consequently the greatest heat production occur in those tissues that have the highest water content. This effect also is enhanced locally in those areas adjacent to bone or tough fascial planes that act as reflective surfaces where standing waves may be set up. (See the interface reflector coefficients in table 3.) Absorption coefficients are high particularly for skin, muscle, and internal organs and are low for bone, fat, and yellow marrow.

Experimental evidence has established that certain organs are more susceptible than others to damage by microwave radiation--in particular, eyes, testicles, gall bladder, urinary bladder, and portions of the gastrointestinal tract. The increased susceptibility is due to a difference in the magnitude of the blood flow, which affects the rate of heat removal from these tissues.

3.1 Thermal Effects on the Eye

The eye is one of the few organs that can be directly exposed to microwaves without the influence of intervening skin and other tissues. The superficial location and the structural characteristics of the eye make it particularly susceptible to microwave injury. There is general agreement that cataractogenesis in humans and animals can be caused by thermal effects due to microwave and radio frequency radiation. What is not clear, however, is whether ocular damage in terms of lens or retinal lesions is possible after chronic exposure to field power densities of an intensity below that which is normally associated with thermally induced effects.[4,6-8]

In addition to the relatively poor blood supply, the cavities near the eye and high electrical conductivity of the intraocular fluids (with the resulting short penetration of the electromagnetic radiation in the eyeball) affect the eye's ability to conduct excessive heat to other parts of the body. The lens, being avascular and enclosed in a capsule, is at a specific disadvantage in not having a cooling (vascular) system. Not having available macrophages to remove dead cells or replacement cells, the lens cannot repair itself as can other body parts. Thus, damage to the lens is generally irreversible. Depending on the dose, the damaged cells slowly lose their transparency. However, opacity may not occur until sometime after exposure.[4,6-8]

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[4] *W. Moore, Biological Aspects of Microwave Radiation: A Review of Hazards, U.S. Department of Health, Education, and Welfare TSB-68-4 (July 1968).*

[6] *Z. R. Glaser and C. H. Dodge, Biomedical Aspects of Radiofrequency Radiation: A Review of Selected Soviet, Eastern European, and Western References, in Biological Effects of Electromagnetic Waves, U.S. Department of Health, Education, and Welfare Food and Drug Administration 77-8010/8011 (1977).*

[7] *S. M. Michaelson, R. A. E. Thomson, and J. W. Howland, Biological Effects of Microwave Exposure, Rome Air Development Center, Rome, NY, RADC-TR-67-461 (September 1976).*

[8] *J. C. Mitchell, Electromagnetic Radiation Effects on the Eye, in Radiation Hazards, North Atlantic Treaty Organization Advisory Group for Aerospace Research and Development, Paris, France, Lecture Series No. 78 (August 1975).*

There have been a large number of experiments performed on animals, particularly rabbits and dogs, in which cataract formation was quantified in terms of temperature rise of the eye, incident power densities, and exposure times. In general, cataracts have been formed as a result of temperature increases of the order of 10 to 20 deg C. Irradiation of various levels, both continuous wave (cw) and pulsed, have been investigated with thresholds for damage appearing to be on the order of one to several hundred milliwatts per square centimeter. The majority of these data have been taken at frequencies around 2 GHz, with some experiments going as high as 24 GHz. The results appear to sustain the view that cataracts are formed due to thermal interactions at relatively high temperatures caused by correspondingly high power densities. There is conflicting opinion concerning the possibility of cumulative damage to the lens from repeated subthreshold irradiation.[4,6-8]

The question of frequency dependence again appears to reduce to a skin effect problem. Thus, in lieu of experimental data to the contrary, one would have to conclude that risk of cataractogenesis from radiation in the NMMW region is less than that from lower frequency radiation.

3.2 Thermal Effects on the Testicles

The testicles are extremely sensitive to elevation in temperature. This sensitivity is due to their external location, the high rate of cell division and differentiation, and the fact that the main route of heat dissipation is through the blood vessels of the scrotal skin. It has been found that spermatogenesis can take place only at temperatures approximately 2 deg C below the normal body temperature. Experiments have been carried out on animals in which heating from lower frequency microwaves caused testicular damage that was, except in severe cases, largely temporary.

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[4] *W. Moore, Biological Aspects of Microwave Radiation: A Review of Hazards, U.S. Department of Health, Education, and Welfare TSB-68-4 (July 1968).*

[6] *Z. R. Glaser and C. H. Dodge, Biomedical Aspects of Radiofrequency Radiation: A Review of Selected Soviet, Eastern European, and Western References, in Biological Effects of Electromagnetic Waves, U.S. Department of Health, Education, and Welfare Food and Drug Administration 77-8010/8011 (1977).*

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[8] *J. C. Mitchell, Electromagnetic Radiation Effects on the Eye, in Radiation Hazards, North Atlantic Treaty Organization Advisory Group for Aerospace Research and Development, Paris, France, Lecture Series No. 78 (August 1975).*

As in the case of eye damage, data on the frequency dependence of testicular damage are lacking, particularly at the higher frequencies. The radiation that causes the thermal effects must be assumed to attenuate from the same skin effects, thus indicating a reduced thermal risk from NMMW radiation.

3.3 Thermal Effects on Other Body Parts

There are many other biological hazards due to thermal effects. A great number of data have been taken, mostly on animals, in various exposure modes (cw and pulsed), at a multiplicity of dose rates and intensities and for periods of time extending to 6 months. However, almost all the experiments were carried out below 3 GHz, with only a few at 10 and 24 GHz. No frequency dependence has been investigated, with the exception of the previously mentioned skin effect calculations, which seem to exclude NMMW radiation as a potential source of thermal hazard.

However, for the sake of completeness, the following is a partial list of some of the specific effects noted by various investigators. All occurred at frequencies below 10 GHz, with most below 3 GHz.

Changes in plasma and tissue trace metals (iron, zinc, calcium, and magnesium)

Weakening of the immune system

Changes in fetal development

Changes in blood pressure

Loss of weight and endurance

Reduction in fertility

Changes in bone marrow

These are just a few of the many examples found in the literature. Intuitively, one should expect such a broad range of effects when various parts of the body are selectively heated by radiation or by any other agent. As has been mentioned several times before, however, the lack of penetration of higher frequency radiation raises the question of whether there are mechanisms other than thermal by which non-ionizing radiation can cause deleterious effects.

4. EXPOSURE OF CRITICAL ORGANS TO NMMW RADIATION: NONTHERMAL EFFECTS

The previous question is the center of the major controversy in the study of biological effects of microwave radiation. If there are such effects that are not related to heating, by what mechanism do they operate? Is it necessary to irradiate the subjects at the same intensities as it is to cause thermal effects?

Many Western investigators are by and large of the opinion that biological effects are strictly thermal in nature and have set their maximum safety standards accordingly. They argue from a large body of experimental data that correlate reasonably well with theories based on calculation of dielectric constants and other physical properties. These theories obviously exclude the possibility of any effects due to radiation much above X-band.

On the other hand, the Eastern European nations and particularly the Soviet Union argue that there are indeed nonthermal effects that occur at intensities far lower than the safety standards set in the United States. The problem with their claims is that the measures of nonthermal effects used are much more subjective and less easily quantified than those of thermal effects. It has been argued in the West that the Soviet reports of nonthermal effects are poorly documented, incomplete in their presentation of experimental methodology and data, and faulty in the interpretation of experimental results or clinical findings.

Nevertheless, Soviet and Eastern European specialists are convinced that electromagnetic fields in the microwave frequency range exert both thermal and nonthermal influences. At higher power densities, the effects are associated with the liberation of heat in biological objects with the resulting heating of organs and tissues and thermal damage. At lower power densities, the physical mechanisms behind the various biological effects are not clear, but it is generally accepted in that community that nonthermal effects do exist.

The following list shows a sampling of effects found by Soviet and Eastern European researchers[7] to occur at power densities of less than 10 mW/cm^2.

Clinical effects in humans

General subjective complaints (sensations, illusions, fatigue, loss of appetite, and asthenia)

Functional central nervous system and perception changes

Cardiovascular and associated autonomic changes

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[7] *S. M. Michaelson, R. A. E. Thomson, and J. W. Howland, Biological Effects of Microwave Exposure, Rome Air Development Center, Rome, NY, RADC-TR-67-461 (September 1976).*

Altered blood chemistry

Altered metabolism

Depressed endocrine function

Increased susceptibility to infectious diseases

Experimental effects in animals

Decreased physical endurance and retarded weight gain (rats)

General inactivation of central nervous system electrical activity, domination of the hypothalmic function, and altered afferent function (rabbits and cats)

Inhibition of conditioned reflexes, increased motor activity, and weakening of excitation and inhibition reactions (rats, mice, and birds)

Altered reactivity in response to drugs (rats and rabbits)

Altered blood pressure and heart rate (rats and rabbits)

Altered blood neuroendocrine chemistry (rats and rabbits)

Altered amino acid and ascorbic acid metabolism (rats)

Altered reproductive cycle and decreased viability of offspring (rats)

Altered immune reactions (rabbits)

Most of the effects reported appear to be reversible. For example, Soviet studies of occuptional workers exposed to microwave power densities generally well below 10 mW/cm^2 continue to report various reversible functional changes in the nervous and cardiovascular systems; these changes lead to a characteristic complex of symptoms. In fact, microwave or radiation sickness has been isolated as a distinct clinical entity in the Soviet Union.

The most intriguing question in regard to nonthermal effects is the possibility of resonances in biological systems occurring in the millimeter region. This question was first examined theoretically by Froehlich in a series of papers. In a recent paper,[9] he summarizes this

[9] *H. Froehlich, Long-Range Coherence Effects in Biological Systems, Rev. del Nuovo Cimento, 7 (1977), 399-418.*

theory. He first recognizes the fact of the tremendous fields existing across cell membranes, on the order of 10^5 V/cm, and the possibility for very large dipole moments as ions are displaced in relation to the membranes by only small amounts. He then calculates two models, the first showing that electric dipole vibrations can be strongly and coherently excited in biological systems when metabolic energy is available and the second showing that biological systems have metastable states with very high E-polarization. From these calculations, several observations are made that strongly indicate the existence of resonance phenomena occurring at high frequencies (about 100 GHz).

The observations that Froehlich made from his calculations were as follows:

a. Both types of excitation--the long range, coherent vibrations and the metastable high polarization states--require a source of activation energy.

b. If an oscillating giant dipole exists, the long range forces caused by it normally are screened by the presence of the considerable number of small ions in the cell water. This screening, however, does not exist at high frequencies (about 100 GHz), where these long range forces may be activated.

c. The interaction energies of the long range forces are shown to be highly frequency selective. Two oscillating giant dipoles of different frequencies at a distance R apart have an interaction energy that goes as $1/R^6$. However, when the two frequencies are nearly equal, the interaction dependence jumps three orders of magnitude to $1/R^3$.

d. There is a critical magnitude of the excitation energy below which the phenomena should not occur. Furthermore, above the threshold, the biological effects predicted should be independent of intensity over a relatively large range.

There are several experimental data that seem to demonstrate effects of a resonance nature by millimeter wave radiation on biological systems. The threshold relation of the radiation intensity, the intensity independence above threshold, and the narrow frequency selectivity all seem to support Froehlich's hypothesis.

Figure 3 shows the frequency dependence of cell division of a yeast culture on radiation around 40 GHz. The ordinate is the ratio of the number of cells in the experiment to the control. It was found that the cell division was stimulated at 7.18 mm (41.8 GHz) and slightly depressed at other wavelengths.[10] This work was repeated in a more

[10] *N. D. Devyatkov, Influence of Millimeter-Band Electromagnetic Radiation on Biological Objects, Sov. Phys. Usp., 16 (1974), 568.*

refined manner by workers at the Max Planck Institute.[11] The results were similar, but the resonances were more highly resolved.

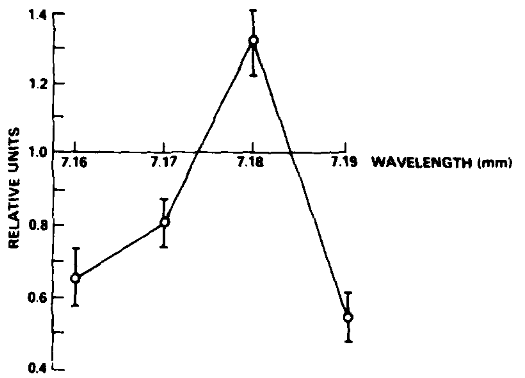

Figure 3. Wavelength dependence of yeast cell division rate on radiation at 40 GHz (from N. D. Devyatkov, Sov. Phys. Usp., 16, 1974, 568).

Sevast'yanova and Vilenskaya[12] performed an experiment on mouse bone marrow cells by irradiation at 42 GHz followed by exposure to x-radiation and then counted the remaining undamaged cells. Power density, exposure time to the microwaves, and wavelength were varied. Figure 4 shows the results of varying the incident intensity. The threshold effect is obvious, occurring at 9 mW/cm^2. Below this level there was no biological effect, and above this level the effects were intensity independent. Also plotted in this figure is the change in skin temperature of the animal during irradiation. That the biological effect does not correlate with the skin temperature indicates a nonthermal process. Figure 5 shows the wavelength (or frequency) dependence of the effect. Both these figures speak for the resonance theory.

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[11] *W. Grundler and F. Keilmann, Proceedings of Third International Conference on Submillimeter Waves and Their Applications, University of Surrey, Guildford, U.K. (29 March-1 April 1978), 296-297.*

[12] *L. A. Sevast'yanova and R. L. Vilenskaya, A Study of the Effects of Millimeter-Band Microwaves on the Bone Marrow of Mice, Sov. Phys. Usp., 16 (1974), 570.*

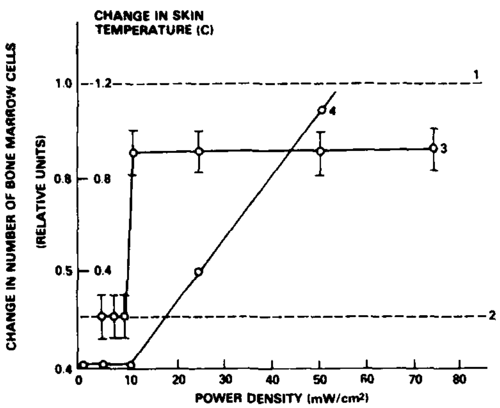

Figure 4. Changes in number of bone marrow cells and skin temperature of irradiated mice as functions of power flux density: (1) number of bone marrow cells (control), (2) exposure to x-radiation, (3) combined exposure to microwaves and x-rays, and (4) change of skin surface temperature (from L. A. Sevast'yanova and R. L. Vilenskaya, Sov. Phys. Usp., 16, 1974, 570).

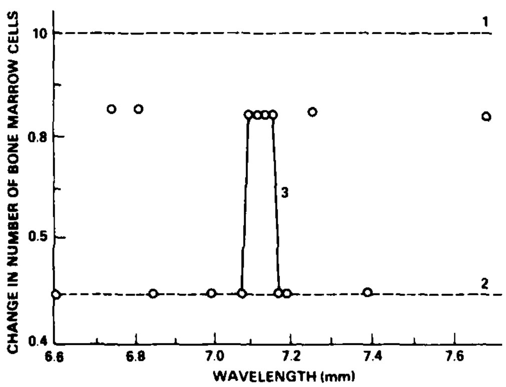

Figure 5. Variation of number of bone marrow cells with wavelength: (1) control (unirradiated mice), (2) x-radiation, and (3) microwave field and x-radiation (from L. A. Savast'yanova and R. L. Vilenskaya, Sov. Phys. Usp., 16, 1974, 570).

A similar experiment was carried out by Smolyanskaya and Vilenskaya[13] in which the effect of microwaves (alone) on colicin synthesis in certain strains of the bacillus Escherichia coli were measured as a function of frequency, irradiation time, and power density. Figures 6 and 7 show results similar to those shown in the previous two figures. There are a number of other Soviet references with similar results, all around 40 GHz. At high frequencies, there are not as much data. However, there is a paper by Webb and Dodds[14] showing a definite slowing down of cell divisions of E. coli B with exposure to 136-GHz radiation.

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[13] *A. Z. Smolyanskaya and R. L. Vilenskaya, Effects of Millimeter-Band Electromagnetic Radiation on the Functional Activity of Certain Genetic Elements of Bacterial Cells, Sov. Phys. Usp., 16 (1974), 571.*

[14] *S. J. Webb and D. D. Dodds, Inhibition of Bacterial Cell Growth by 136 Gc Microwaves, Nature, 218 (1968), 374.*

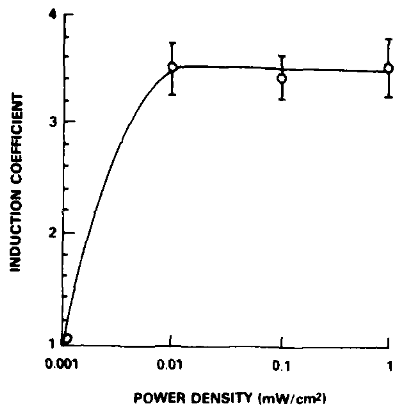

Figure 6. Induction coefficient of colicin synthesis as function of power density (from A. Z. Smolyanskaya and R. L. Vilenskaya, Sov. Phys. Usp., 16, 1974, 571).

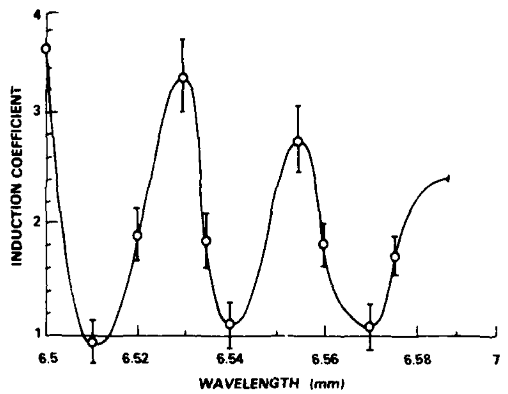

Figure 7. Induction coefficient of colicin synthesis as function of wavelength (from A. Z. Smolyanskaya and R. L. Vilenskaya, Sov. Phys. Usp., 16, 1974, 571).

In the 70-GHz region, Berteaud et al[15] plot the effects that they measured on a colony of E. coli along with similar results by Webb and Booth.[16] Figure 8 shows these results with two resonances, one at 73 GHz and one between 70.5 and 71 GHz.

A large number of seemingly nonthermal (power densities as low as 5 μW/cm^2) effects observed by Soviet and other Eastern Bloc researchers are reported in a Defense Intelligence Agency report.[17] Most of the effects, however, are observed at lower frequencies (<3 GHz), and the authors, unfortunately, do not provide references for the reported experiments. The report does indicate the broad interest in this area within the Soviet sphere of influence.

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[15] *A. J. Berteaud, M. Dardalhon, N. Rebeyrotte, and D. Auerbeck, C. R. Seances Soc. Biol. Paris, 281D (22 September 1975), 843-846.*

[16] *S. J. Webb and A. D. Booth, Nature, 222 (21 June 1969), 1199-1200.*

[17] *R. L. Adams and R. A. Williams, Biological Effects of Electromagnetic Radiation (Radiowaves and Microwaves)--Eurasian Communist Countries (U), Defense Intelligence Agency DST-1810S-074-76 (March 1976). (CONFIDENTIAL--NO FOREIGN DISSEMINATION)*

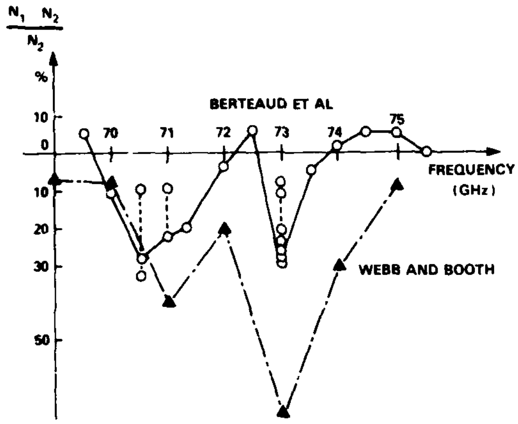

Figure 8. Variation with frequency of relative difference between number of irradiated colonies in solution and control (from A. J. Berteaud et al, C. R. Seances Soc. Biol. Paris, 281D, 1975).

5. CONCLUSIONS: THE QUESTION OF STANDARDS

The decisions facing the microwave, millimeter wave, and NMMW communities today center on the following questions:

Are there hazards from microwave radiation?

Are the hazards nonthermal as well as thermal in nature?

What are the physical mechanisms of the hazards?

What are the appropriate standards to be set for the safety of personnel working in the field?

The answers to these questions provide a summary of this report. Yes, there are definitely hazards, and a major category is the thermal hazard whose physical mechanism is primarily by raising the body temperature. There is also the occurrence of secondary thermal effects. However, there appears to be sufficient evidence, albeit qualitative, to say that there are nonthermal hazards also. Their physical coupling to a biological organism is not clear by any measure. Froehlich's arguments explain the observed resonances on the quantitative level, but tell us nothing of why a yeast culture should grow faster or slower under irradiation. He also makes some remarks on causes and cures for cancer,[9] but again this is all in the realm of speculation, although intuitively one could accept some sort of causal relationship in principle.

[9] *H. Froehlich, Long-Range Coeherence Effects in Biological Systems, Rev. del Nuovo Cimento, 7 (1977), 399-418.*

Of more immediate interest to the readers of this report is the question of frequency dependence. While the existence of all sorts of hazards can be accepted at lower frequencies where the skin depth allows penetration to the vital organs and the central nervous system, in the NMMW region (100 to 1000 GHz) the skin depth is so small that any hazard seems to be limited to the outer surface of the body. Even the eyes do not appear to be as vulnerable to thermal effects since the cataracts form within the lens structure, not on the surface.

Thus, one is forced to conclude at this time that the NMMW region may not possess any significant risk, at least not unless some mechanism for the interaction of the radiation with the body is found. Froehlich[9] suggests the possibility of energy transfer from the outer surfaces inward. One could even speculate on some unusual feedback mechanisms between the nerve endings near the skin surface and the central nervous system. Also, as has been mentioned earlier, the possibility of resonance coupling with the smaller external parts of the body (as opposed to the whole body) must not be dismissed.

In terms of standards, table 4 presents a comparison of the current standards in use in various countries. It is evident that the USSR and Eastern European countries are considerably more conservative than the United States.[18] There is currently considerable pressure to make our standards more stringent, and it appears that the Environmental Protection Agency is going to take steps to do so next year, the reduction to be probably one order of magnitude. One of the moving forces behind this action was the publication of Paul Brodeur's somewhat sensationalistic book, The Zapping of America.[19]

As noted above, the NMMW region appears to cause no problem, but in matters of safety, if one must err, it is obviously better to err on the side of caution.

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[9] *H. Froehlich, Long-Range Coherence Effects in Biological Systems, Rev. del Nuovo Cimento, 7 (1977), 399-418.*

[18] *S. M. Michaelson, Microwave Standards--A Comparative Analysis, University of Rochester, Rochester, NY, AEC UR-49-1080 (1969).*

[19] *P. Brodeur, The Zapping of America, W. W. Norton Co., New York (1977).*

TABLE 4. RECOMMENDED MAXIMUM PERMISSIBLE INTENSITIES FOR RADIO FREQUENCY RADIATION

Maximum permissible intensity	Frequency (MHz)	Country or source	Specifications
10 mW/cm^2	10 to 100,000	U.S.A.S.I., 1966; Canada, 1966	1 mWh/cm^2 for each 6 min
	30 to 30,000	Great Britian, 1960	Daily exposure
	1000 to 3000	Schwan and Li, 1956	Whole body
	All	U.S. Army and Air Force, 1965	10 mW/cm^2 continual exposure
			10 to 100 mW/cm^2 limited occupational exposure
		Sweden, 1961	Occasional occupational exposure
		Federal Republic of Germany, 1962	--
1 mW/cm^2	700 to 30,000	U.S. electronics and communications industry, 1956	Whole body
	All	Sweden, 1961	General public; prolonged occupational exposure
	>300	USSR, 1965; Poland, 1961	15 to 20 min/day
0.5 mW/cm^2	All	North Atlantic Treaty Organization, 1956	--
0.1 mW/cm^2	>300	USSR, 1965; Poland 1961	2 to 3 hr/day
0.025 mW/cm^2	>300	Czechoslovakia, 1965	Continuous wave 8 hr/day
0.01 mW/cm^2	>300	USSR, 1965	6 hr/day
		Poland, 1961	Entire day
		Czechoslovakia, 1965	Pulsed 8 hr/day
20 V/m	0.1 to 30	USSR, 1965	--
10 V/m	0.01 to 300	Czechoslovakia, 1965	Pulsed 8 hr/day
5 V/m	30 to 300	USSR, 1965	--

Source: S. M. Michaelson, University of Rochester, Rochester, NY, AEC UR-49-1080 (1969).

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(9) H. Froehlich, Long-Range Coherence Effects in Biological Systems, Rev. del Nuovo Cimento, 7 (1977), 399-418.

(10) N. D. Devyatkov, Influence of Millimeter-Band Electromagnetic Radiation on Biological Objects, Sov. Phys. Usp., 16 (1974), 568.

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